

NMR of superfluid ^3He in anisotropic aerogel

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We report on orientation of the order parameter in the ^3He -A and ^3He -B phases caused by aerogel anisotropy. In ^3He -A we have observed relatively homogeneous NMR line with an anomalously large negative frequency shift. We can attribute this effect to an orientation of orbital momentum along the axis of density anisotropy. The similar orientation effect we have seen in ^3He -B. We can measure the A-phase Leggett frequency, which shows the same energy gap suppression as in the B-phase. We observe a correlation of A - B transition temperature and NMR frequency shift.

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INTRODUCTION

Pure superfluid ^3He is certainly one of the most complex systems in condensed matter which can be successfully described by a comprehensive theory. The influence of disorder on ordered states is one of the most interesting and ubiquitous problems in condensed matter physics. In the case of superfluid ^3He the disorder can be produced by its impregnation in high porosity silica aerogel. It was found, that the aerogel disorder leads to significant changes of phase diagram of superfluid ^3He . Not only the critical temperature changes, but also the ground states of A and B phases as well the temperature and dynamics of transition between them. There is not yet conclusive description of A like state in aerogel. It can be "Robust" or "No-Robust" state [1, 2]. D.D.Osheroff [3] suggested that the A-like phase is a "Planar" phase, while Kyoto theoretical group [4] suggested a "Polar" like state for anisotropic aerogel.

Particularly interesting is the question of the influence of a local random anisotropy of aerogel on the superfluid ^3He -A order parameter. The orbital part of the order parameter suppose to be very sensitive to the anisotropy of aerogel density. The short scale anisotropy can leads to a Larkin-Imry-Ma state as shown in a resent work by Volovik [5]. The anisotropy of scale longer then texture healing length can leads to a texture and NMR inhomogeneity. The global anisotropy can orients the order parameter throw out of the sample. The question of natural aerogel anisotropy is now under intensive investigations [6]. The global anisotropy can be achieved by aerogel deformation owing to the uniaxial pressure and can lead to appearing a new phase, as suggested in [4].

A related problem is the formation of topological defects and disorder after a broken symmetry transition [8, 9]. It was thought that in bulk ^3He the disorder and

topological defects can easily disappears after transition. In fact, some types of defects rest inside the superfluid ^3He even in the bulk conditions [10]. In the superfluid ^3He in aerogel the topological defects can be pinned. This provides an interesting example of a system with continuous symmetry in the presence of random anisotropy disorder. It was suggested to describe it, at least ^3He -A, as the the Larkin-Imry-Ma state, contaminated by the network of the topological defects pinned by aerogel [5]. The experimental evidence of topological defects contamination in ^3He -B have been found in Grenoble [11]. There was shown that the NMR signal is a superposition of the signals with different properties. Similar observation for ^3He -A was recently described in ref. [12].

Both these problems are illuminated by investigations we presented in this article. First of all we pay attention to the fact that the orientation of orbital part of order parameter is very sensitive to the density anisotropy of aerogel. Its oriented along a direction, in which the concentration of aerogel is bigger. According to G. Volovik estimations [5, 7] the aerogel linear deformation of order of 0.1% can leads to a regular orientation of the order of parameter in ^3He -A. We have performed our experiments with superfluid ^3He in aerogel under an axial deformation, and found that the orbital momentum of superfluid A and B phases is oriented along the axis of deformation. In result of this orientation, the NMR of A phase display a large negative frequency shift, while the NMR signal from B phase remains in vicinity of the Larmor frequency. We can see the broadening of NMR line, which is likely the effect of inhomogeneity of aerogel local density orientation. Owing the negative frequency shift for A phase, we was able, in a first time, to observe the dependance of A-B transition temperature on the NMR frequency shift. This effect can bring us a new ideas about mechanism of A-B transition in aerogel. We have seen a very small influence of rotation on the NMR signals, and only in

the case, when we cross T_c under fast rotation. We can suggest that the main part of aerogel is contaminated by the network of the topological defects pinned by aerogel.

EXPERIMENTAL SETUP

Our experiments were done at pressures 29.3 bar in magnetic field of 290 gauss, corresponding to NMR frequency of 940 kHz. We used the aerogel sample of 98% porosity aerogel in a form of cylinder (diameter=5mm, length=3 mm) with the axis oriented along the external steady magnetic field. The sample was kindly made by N. Mulders. It was placed inside the Stycast 1266 epoxy cell. In the first set of the experiments the aerogel fit loosely in the cell except for a some force applied by the top and bottom of the cell, which deformed the aerogel in the direction of the magnetic field and removed any gap between the aerogel and top and bottom of the cell. With cooling the Stycast body constrain on about 1% more then aerogel itself. Consequently, we can suppose that the aerogel sample is deformed in a few percent in a direction of external magnetic field. In a second set of experiments the additional Stycast constrain was removed. By analyze of our results, we can conclude, that the global orientation remains, but decrease. The influence of Stycast constrain on order parameter orientation is clearly seen.

The cell was connected to the rest of ^3He by a channel of 1 mm. in diameter. The thermometry was done on the basis of a melting curve thermometer. In order to avoid the formation of solid ^3He on the surface of aerogel strands, we have preplated aerogel by ^4He . The cell was installed on a rotating nuclear demagnetization cryostat of ISSP, Tokyo university. Its give us ability to check the influence of rotation on the observed NMR signals. We have used the usual CW NMR spectroscopy as well the Homogeneous Precessing Domain (HPD) method of NMR [13].

EXPERIMENTAL RESULTS

The NMR signals, we have observed at cooling, is shown in Fig.1. In comparison with previous publications, we have observed in A-like phase a relatively narrow NMR line with a big negative NMR frequency shift. We can attribute it to the global orientation of orbital momentum in ^3He -A along the magnetic field. Below 0.82 of the transition temperature in aerogel (T_c^a) the part of ^3He make a transition to B phase. We have found that at the conditions of our experiments the positive NMR shift of ^3He -B is very small. This results show that orbital momentum in ^3He -B also globally oriented along the magnetic field! In Fig.2 we show the frequency shift for the maximum of the NMR lines as well the left

edges of the line for A like and B like phases. We are also shows the frequency shift for the second run, when the cell pressure was released.

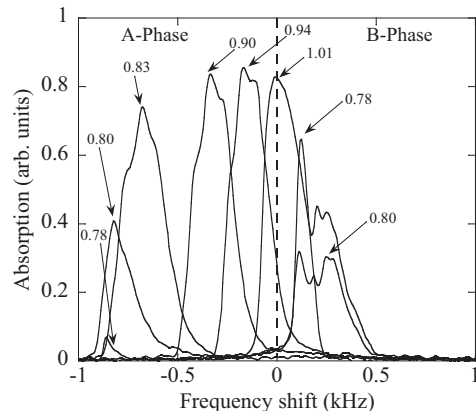


FIG. 1: The signals of CW NMR for different temperatures (in units T_c^a) shown by number for each curve. The signals with negative frequency shift corresponds to ^3He -A and with positive frequency shift - to ^3He -B.

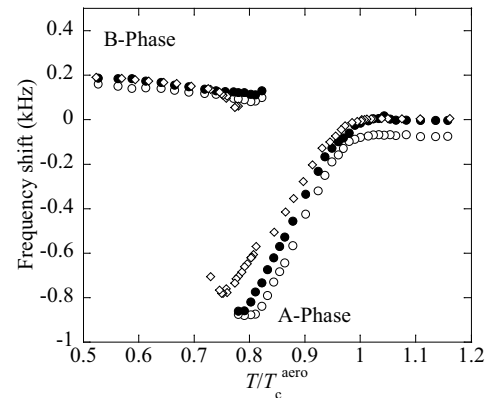


FIG. 2: Position of the left edge (○) and the maximum (●) of NMR line for the run with pressure and maximum (◇) for the run without additional pressure.

The transverse NMR frequency in A phase in the bulk depends from the orientation of orbital momentum vector \mathbf{L} and spin vector \mathbf{d} .

$$\omega^2 = \omega_l^2 + \Omega_A^2 \cos(2\phi), \quad (1)$$

where ω_l is the Larmor frequency, Ω_A is the Leggett frequency in A phase and ϕ is the angle between \mathbf{L} and \mathbf{d} . At the magnetic fields we have applied, the spin vector \mathbf{d} should be oriented perpendicular to \mathbf{H} . The maximum negative NMR frequency shift corresponds to the orientation of \mathbf{L} along the magnetic field. If we have reached the vertical orientation of \mathbf{L} , and if A like phase in aerogel is ABM state, then the ratio of Ω_B/Ω_A for the aerogel should be the same as for the bulk case. The Ω_B in

aerogel have been studied by different methods in [14]. From these data we can estimate Ω_B in aerogel at 29.3 as a 0.5 of Ω_B in a bulk. In Fig.3 we show the Ω_A in a bulk by dashed line, and its 0.5 value by dotted line. We have found that at low temperatures the measured Ω_A (●) are approaches to dotted line and corresponds to ABM state in aerogel. At a temperatures above $0.9 T_c^a$ the measured Ω_A is significantly low. Can it be the error of the method? Part of NMR shift can be hidden by NMR broadening. To estimate this, we have calculated Ω_A as a shift from the center of a normal ^3He NMR line to a left edge of A-phase line (○). It is clearly seen that this effect can explain the deviation only near T_c^a . At the temperature region from 0.97 to 0.88 T_c^a the deviation of Ω_A from the value suggested by ABM state is clearly seen! It may be that the order parameter changes smoothly from planar to ABM state at cooling. This our observation would be interesting to check by other methods.

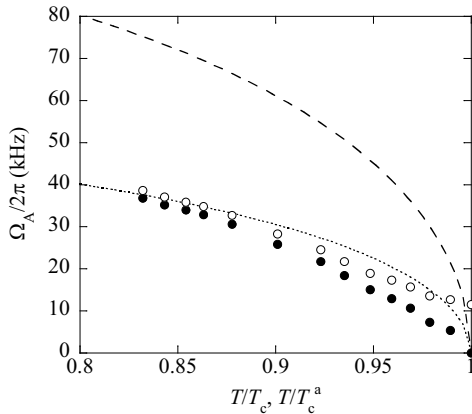


FIG. 3: The Ω_A calculated by the NMR shift from the left edge (●) and from the maximum of NMR line (○) of normal ^3He . The dashed line shows the value of Ω_A for bulk ^3He , shown in temperature scale of T_c bulk. Dotted line, the half of Ω_A for bulk shown in scale of T_c in aerogel.

We are clearly seen that the transition temperature from A to B phase depends on the frequency shift in $^3\text{He-A}$! Previous studies show that the A and B phases can coexist in some range of temperatures [15–17]. But there was not known, what parameter controls the temperature of this transition for different parts of the sample. We found that at cooling the part of $^3\text{He-A}$ with larger frequency shift going to transition in a first. (See Fig.1 and Fig.2) For the second set of experiments without Stycast constrain the effect is even more profound. The bigger angle of deviation of \mathbf{L} from the magnetic field, the smaller frequency shift and lower the temperature of transition. We have succeed to observe this effect owing the negative frequency shift of NMR. In a usual case of positive NMR shift for A phase it was difficult to separate well A and B phase signals. We call theoreticians

for to explain the dependance of A-B transition temperature from \mathbf{L} orientation. The alternative explanation can be made, if one suggest the distribution of aerogel density. The regions with higher density can have lower T_c^a lower temperature of A-B transition and smaller negative frequency shift. For to explain our results from a single run it should be of the order of 10%, that is possible. But with the anisotropic deformation on 1% its should be also changed on about 10%, (see Fig.2) which completely exclude this explanation.

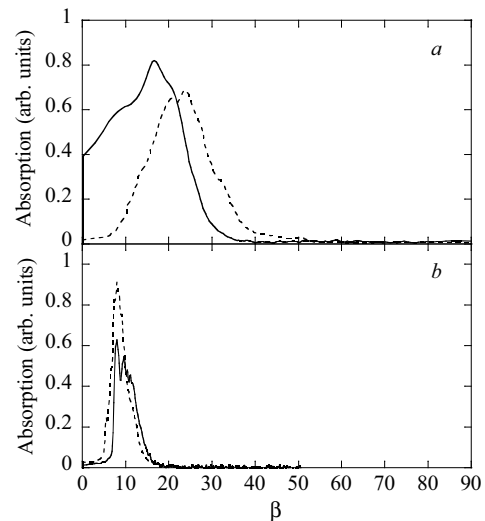


FIG. 4: The distribution of NMR signal in the A (a) and in the B (b) phases presented as function of angle of deflection \mathbf{L} from a vertical direction in a local NMR approximation. The solid line shows the signal from the run with Stycast constrain, dashed line - the signal after the pressure release. The shift from zero degree for B phase can be due to Spin Waves modes in an inhomogeneous order parameter.

We keep in mind the next scenario of aerogel density inhomogeneity and anisotropy: There are a short scale averaging (about of a few coherence lengthes), middle scale (about a few micron, the healing scale in $^3\text{He-A}$), long scale (about a few hundreds micron, the healing length in $^3\text{He-B}$) and a global anisotropy. The first one determines the T_c shift and Imre-Ma state, described above. The middle scale anisotropy averaging determines the local orientation of order parameter in A-phase, and the long scale anisotropy determines the local orientation of order parameter in B phase. The global anisotropy determines the global orientation of the order parameter. We can suppose that in aerogel the density anisotropy oriented randomly. (If it was not oriented at the process of drying, see[6]) Its scattering decrease with increasing of dimensions of averaging. After the first pressure treatment, which reaches the plastic deformation limit, the global density orientation became along the axis of pressure, but with a significant random deviation in a perpendicular plain. The additional pressure due to Stycast

constrain, make orientation more parallel to axis, but after its release the scattering restored.

We can characterize the shape of ^3He -A NMR line in a local approximation; that means that we attribute the local NMR frequency to a local orientation of \mathbf{L} which aligns with the density orientation averaged on a distance of texture healing length. In Fig.4 one can see the deflection of \mathbf{L} from vertical to 25° for this approximation. In the second run, which we have made after Stycast pressure release, the deviation of \mathbf{L} from vertical orientation in A phase significantly increases. Take in mind that Stylist gives an additional 1% axial deformation, we can estimate the global orientation without Stycast pressure on about 3% and the local density anisotropy on the order of 1% and randomly oriented.

We can support this our vision by the data for B phase. The healing length of the texture in B phase is much bigger than in A phase. The averaging on large scale makes density random orientation very small. That is why the B phase shows near vertical orientation of averaged \mathbf{L} for a both cases. The small deviation from zero frequency shift can be explained by the well known shift due to Spin Waves, which we can not take into account in our local approximation.

We have performed many different rotation experiments. We have cooled through the transition under rotation or just rotated at constant temperature or rotated with creation of the HPD. From these experiments we conclude that influence of counterflow is very small for the case of density anisotropy of the aerogel. The same influence can be seen if we will cross T_c^a under rotation. In this case the spin waves modes clearly seen in B phase [18]. The effect of counterflow, observed in [19] can also be seen but a very small amplitude. In A phase the formation of magnetic coherent quantum state have been observed, which we will discuss elsewhere. In brief, the aerogel in our case is saturated by different types of topological defects, but counterflow at T_c^a can prevent the formation of some types of topological defects, which makes order parameter more sensitive to counterflow and to nonlinear NMR.

DISCUSSION AND CONCLUSIONS

For to make a long story short, we have demonstrated in a first time, that the global anisotropy of aerogel has a strong effect on the orientation of orbital momentum in A and B phases. In both phases the orbital momentum is oriented along the direction of compression. The line broadening in ^3He -A is bigger than in ^3He -B due to the difference of texture healing length.

We can put a new light on the problem of aerogel surface orientation. It was found [14] that the free surface of

aerogel orient \mathbf{L} in B phase parallel to the surface. From our results this effect can be explained by a local aerogel deformation at the process of mechanical cutting of the sample. The mechanical treatment can form a dense layer of aerogel near the surface, which orient \mathbf{L} , not a boundary itself.

And finally, we have found that the Leggett frequency dependence does not correspond to one suggested for A phase at the region of temperature down to 0.9 T_c . The discrepancy is much larger than the possible experimental error. Perhaps near T_c the A phase has some kind of planar phase distortion as it takes place with A phase near the wall!

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